IBM TJ Watson Research Center - Advanced Compiler Technologies

Towards a portable OpenMP data sharing implementation for NVIDIA accelerators in the CLANG/LLVM toolchain

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What this talk is about

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- Introducing a **new,** “upstream-able” data sharing scheme for CLANG/LLVM trunk (not to be confused with the current implementation).
- In the current talk we cover only the **first level of sharing**: from one thread in an OpenMP team to the rest of the threads in the team.
- Overcoming the problem that:

“In certain use cases, OpenMP’s **default sharing of local variables** is incompatible with the **default allocation into local memory** of local variables on NVIDIA GPUs.”

Mapping OpenMP to GPUs

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```
void test(){
  int c = 5000;
  #pragma omp target
  {
    c += 1;
    #pragma omp parallel for
    for (i) {
      A[i] = c * i;
    }
  }
}
```

OpenMP allows nesting of regions with different numbers of threads.

Mapping OpenMP to GPUs

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OpenMP semantics

```
void test(){
  int c = 5000;
  #pragma omp target
  {
    c += 1;                    1 thread
    #pragma omp parallel for
    for (i) {
      A[i] = c * i;         all threads
    }
  }
}
```

Mapping OpenMP to GPUs

We need to share "c"

```
void test(){
  int c = 5000;
  #pragma omp target
  {
   c += 1;                    1 thread
    #pragma omp parallel for
    for (i) {
      A[i] = c * i;           all threads
    }
  }
}
```

Mapping OpenMP to GPUs

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Default NVPTX backend policy: "c" is allocated onto the thread local stack

```
void test(){
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```

Mapping OpenMP to GPUs

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  #pragma omp target
  {
   c += 1;                      1 thread
    #pragma omp parallel for
    for (i) {
      A[i] = c * i;             all threads
    }
  }
}
```

On GPUs threads cannot share a variable allocated on the local stack.

Function outlining

- In general: **OpenMP regions** delimited by different constructs will be outlined.
- The master thread assigns those regions to workers **dynamically: we therefore avoid dynamic thread launch in favour of dynamic work allocation to existing threads**.
- Outlining ensures that all parallel OpenMP regions have access to all the worker threads including OpenMP regions that are defined in other compilation units.
- **Data must be shared across multiple functions.**

OpenMP outlined regions example

```
void test(){
  int c = 5000;
  #pragma omp target
  {
    c += 1;                    MASTER
    #pragma omp parallel for
    for (i) {
      A[i] = c * i;            WORKERS
    }
    c += 2;                    MASTER
  }
}
```

Changes to CLANG and the runtime

- The runtime maintains a list of references to the shared variables.
- The MASTER region needs to initialize this list.
- The WORKER region retrieves the list from the runtime and passes the arguments to the outlined parallel region (in the expected order).

Mapping OpenMP to GPUs

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allocated in the
MASTER thread's
local memory by default,
BUT
must now be
"shareable"
with the WORKERS!

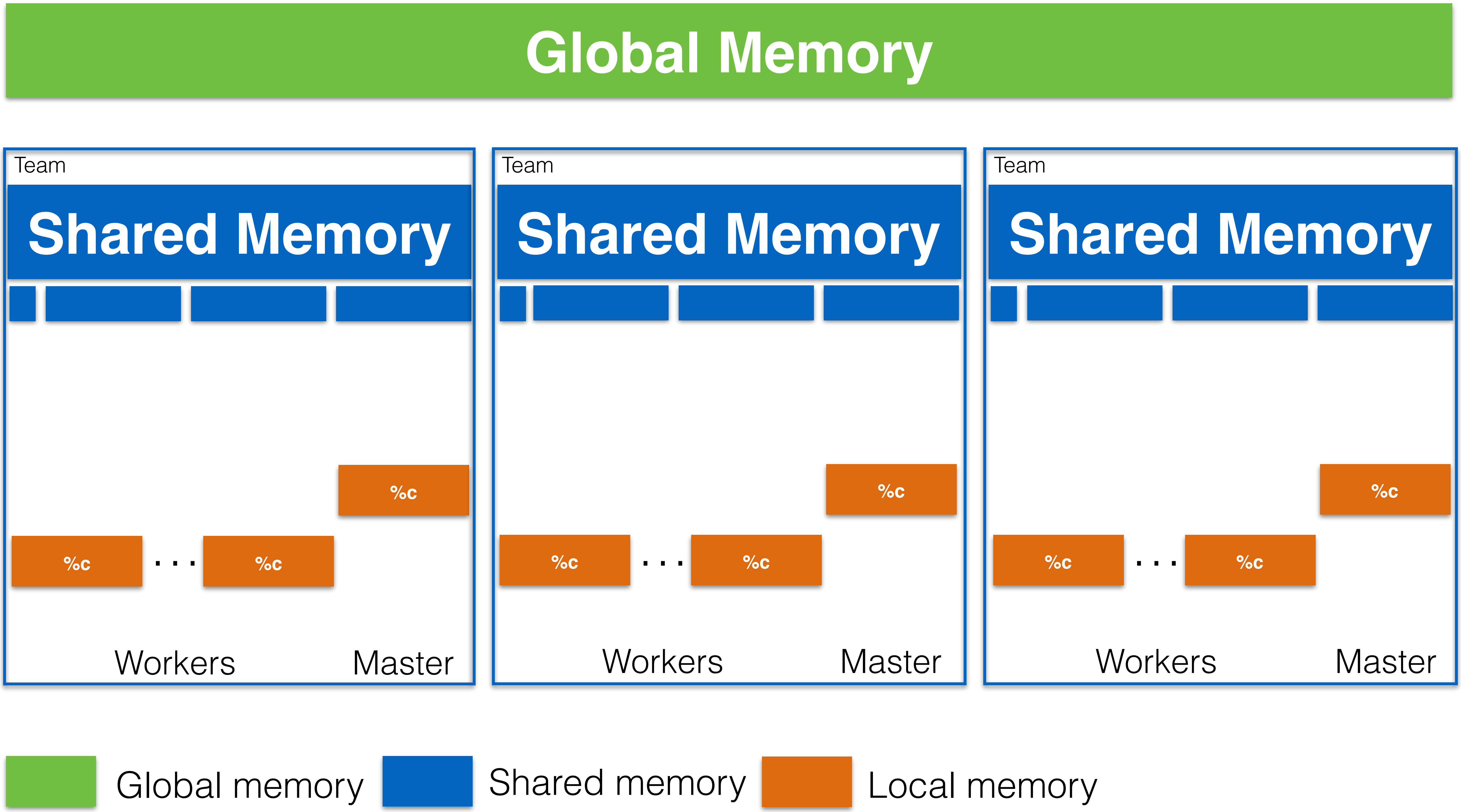
```
void test(){
  int c = 5000;
  #pragma omp target
  {
    c += 1; // LLVM-IR: %c = alloca i32
    #pragma omp parallel for
    for (i) {
      A[i] = c * i;
    }
    c += 2;
  }
}
```

1. In the CUDA model shared variables must be explicitly declared as __shared__.
2. On a GPU, variables allocated in local memory cannot be shared.

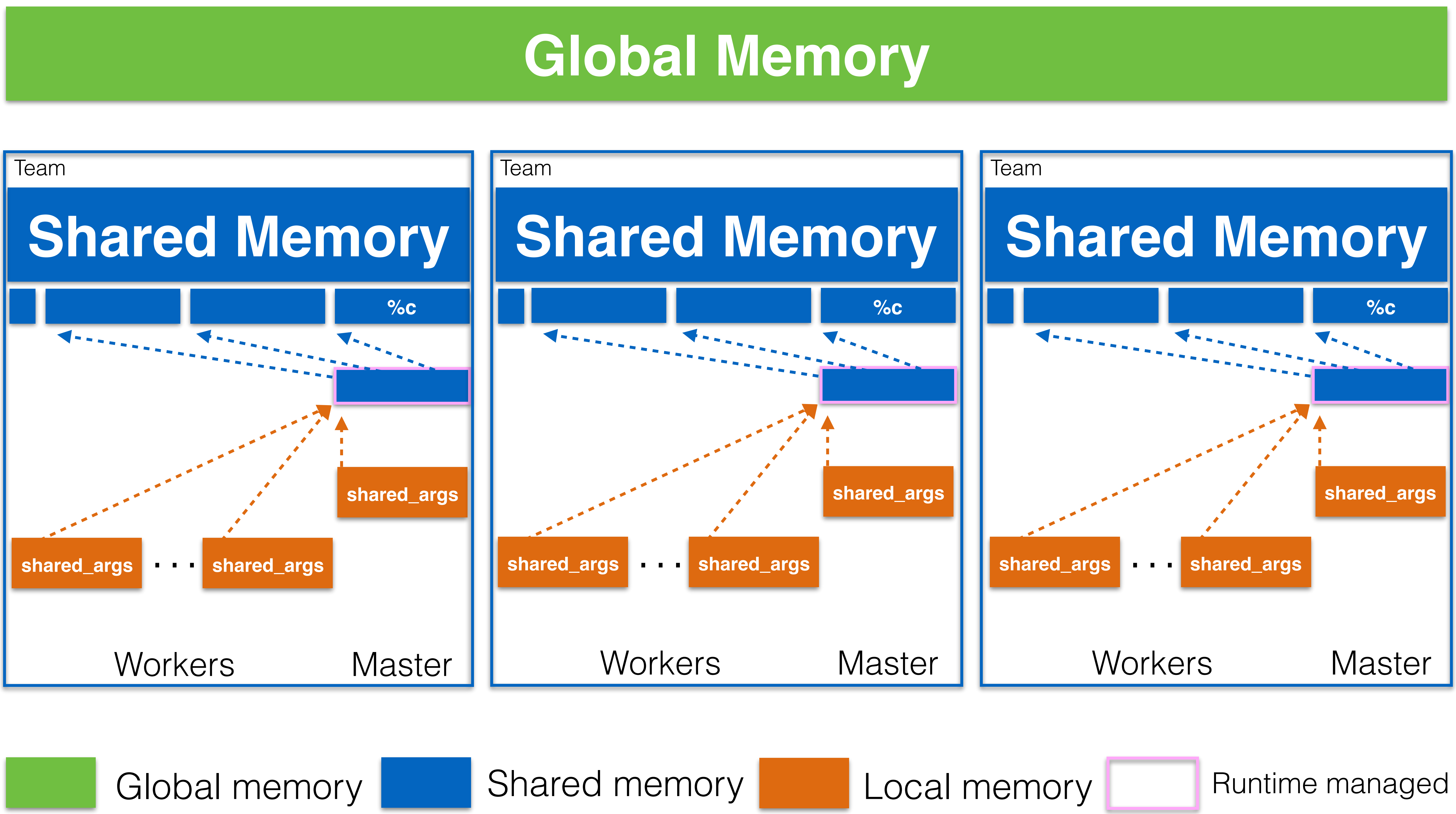
Changes to LLVM's NVPTX Backend

- There are 4 alternative ways for lowering a shared variable:
  - lower alloca to local memory - no sharing needed;
  - lower alloca to shared memory - one instance of the shared variable per team, store variable in shared memory stack, limited by shared memory size;
  - lower alloca to global memory - one instance per team but in global memory, no more team-level management of the variable, vulnerable to recursive functions;
  - lower alloca to runtime-managed memory - use a global memory stack managed by the runtime, supports all cases, interactions with runtime are expensive.

No Sharing


Global Memory
Team
Shared Memory
%c
%c
. . .
%c
Workers
Master
Team
Shared Memory
%c
%c
. . .
%c
Workers
Master
Team
Shared Memory
%c
%c
. . .
%c
Workers
Master
Global memory
Shared memory
Local memory

Shared Memory Scheme



Change address space

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- Introduce a new LLVM-IR pass which will recognize the cases where an alloca should use shared memory instead of local. Detection condition:
  - if an alloca has its address taken i.e. the alloca address is stored
- Insert two address space cast instructions from generic to shared and from shared to generic.

```
%a = alloca i32

…

store i32* %a, i32** %2
```

▶

```
%a = alloca i32
%1 = addrspacecast 0 to 3
%2 = addrspacecast 3 to 0

…

store i32* %a, i32** %2
```

Use a shared stack

- We need to change some of NVPTX's passes over the LLVM, Machine Instruction and PTX intermediate representations:
  - Introduce a new depot in the prologue of the kernel function for the allocation of shared variables.
  - Introduce a shared stack pointer which mimics the way the local stack pointer is set up in the entry block.

Use a shared stack

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- Extend lowering of **alloca**'s to shared memory:
  - **SP** for **generic** address space operations.
  - **SPL** for **local** address space operations.
  - **SPSH** for **shared** address space operations.

```
kernel() {
 .local  .align 8 .b8 __local_depot[10]
 .shared .align 8 .b8 __shared_depot[10]

 mov.u64            %SPL, __local_depot
 mov.u64            %SPSH, __shared_depot
 cvta.local.u64     %SP, %SPL
 cvta.shared.u64    %SP, %SPSH

 add.u64            %rd1, %SPSH, 8
 ld.shared.u64      %rd2, [%rd1]
 …
}
```

PTX

Propagate use of shared stack pointer

- Add a new pass to the NVPTX that will lower the frame index of shared values to the shared stack pointer (SHSP).
- This pass operates on the internal representation of NVPTX (MI - Machine Instruction).

```
%vreg25<def> = LEA_ADDRi64 <fi#3>, 0;
%vreg6<def> = cvta_to_shared_yes_64 %vreg25<kill>;
```

MI - IR

```
%vreg25<def> = LEA_ADDRi64 %VRShared, 32;
```

MI - IR

Putting it all together

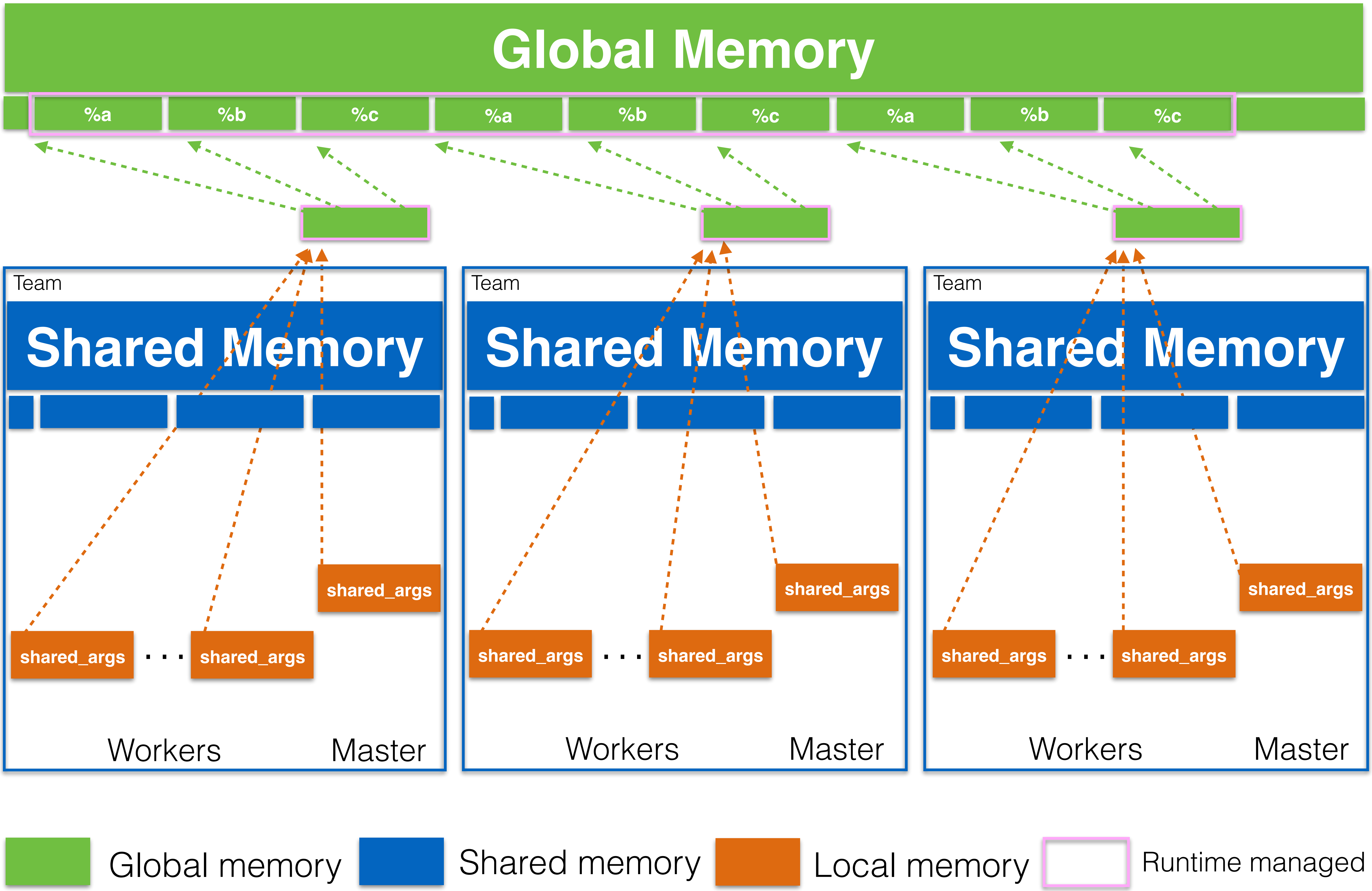
- Addition of a shared memory scheme compatible with the current code generation scheme:
  - we modified the runtime to share values from MASTER to WORKER threads.
  - we modified CLANG's code generation to support our data sharing convention.
- Sharing relies on variables being stored in a "shareable" memory address space on the device:
  - we modified LLVM's NVPTX Backend to support the lowering of shared variables to the GPU's shared memory.

Limitations & future work

- Limitations of the **new** data sharing scheme:
  - **No communication from CLANG to LLVM about OpenMP:** CUDA and OpenMP offloading share the same toolchain, distinguish between the two.
  - **Shared memory is limited:** adopt one of the more generic sharing alternatives for cases in which shared memory is insufficient or inefficient due to occupancy.
  - **Support for recursive functions**
  - **Support second level of sharing among WORKERS:** currently the new data sharing infrastructure only supports sharing from MASTER to WORKERS.
- These limitations do not apply to the current data sharing scheme.

Thank you for listening!
Questions?

Future Work: Global Memory Scheme



Future work: sharing among workers

```
void test(){
  int c = 5000;
  #pragma omp target
  {
    c += 1;
    #pragma omp parallel for
    for (i) {
      int d;
      d = c * i;
      #pragma omp simd
      for (j) {
         B[j] = d * j;
      }
    }
    c += 2;
  }
}
```